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Averaging-free Vector BOTDA assisted by a Reference Probe Lightwave

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Abstract: We propose and experimentally demonstrate an averaging-free vector BOTDA system, which enables both distributed Brillouin gain and Brillouin phase shift detection without trace averaging. A 4m spatial resolution over 18.3 km is realized.

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1. Introduction

Brillouin Optical Time Domain Analyzer (BOTDA) is one of the most focused distributed optical fiber sensing techniques and much effort has been made to enhance its performance. In the past few years, coherent detection has been introduced in BOTDA for signal-to-noise ratio (SNR) enhancement and Brillouin phase shift detection. [1-4] The SNR enhancement allows the system to provide better spatial resolution, longer sensing range, and so on. Brillouin phase shift detection enables dynamic measurement, and also increases the tolerance to non-local effect. [5, 6]

Recently, we reported a coherent BOTDA system without trace averaging. [7] It utilizes a separate local oscillator (LO) generated by single sideband (SSB) modulation from the same laser source, and increases the SNR to avoid the need of trace averaging. However, Brillouin phase shift cannot be detected based on it, as the probe and the LO are generated and transmitted separately, which introduces significant phase distortion and phase noise. Here, we propose an improved scheme to realize an averaging-free vector BOTDA by introducing a reference probe lightwave.

2. Principle and Experimental Setup

The basic principle of the proposed scheme, as shown in Fig. 1 (a), is to generate a reference probe light together with the scanning probe light, so that the phase distortion and noise between the LO and the scanning probe can be estimated by analyzing the beating signal of the LO and the reference light. In this way, the Brillouin phase shift signal carried by the scanning probe light can be resolved. The signals at the two intermediate frequencies are given as

$$I_{\mathrm{S}} \propto R\sqrt{\frac{P_{\mathrm{S0}}\exp(-\alpha L)\left(1+G_{\mathrm{B}}(t)\right)P_{\mathrm{LO}}}{2}}\exp\left[j\left(2\pi f_{\mathrm{IF1}}t+\varphi_{\mathrm{S0}}-\varphi_{\mathrm{LO}}+\varphi_{\mathrm{B}}(t)+\varphi_{\mathrm{N}}\right)\right]+\mathrm{c.c} \quad (1)$$

$$I_{\mathrm{R}} \propto R\sqrt{\frac{P_{\mathrm{R0}}\exp(-\alpha L)P_{\mathrm{LO}}}{2}}\exp\left[j\left(-2\pi f_{\mathrm{IF2}}t+\varphi_{\mathrm{R0}}-\varphi_{\mathrm{LO}}+\varphi_{\mathrm{N}}\right)\right]+\mathrm{c.c} , \quad (2)$$

where P_{S0}, P_{R0}, P_{LO} are the original powers of the scanning probe, reference probe and the LO, R is the responsivity of the detector, α is the fiber attenuation coefficient, L is the fiber length, $G_{\mathrm{B}}(t)$ and $\varphi_{\mathrm{B}}(t)$ is respectively the Brillouin gain and phase shift signal, φ_{S0}, φ_{R0}, and φ_{LO} are the constant phase shifts of the scanning probe, reference probe and the LO light, φ_{N} is the phase noise between the LO and the scanning or the reference probe.

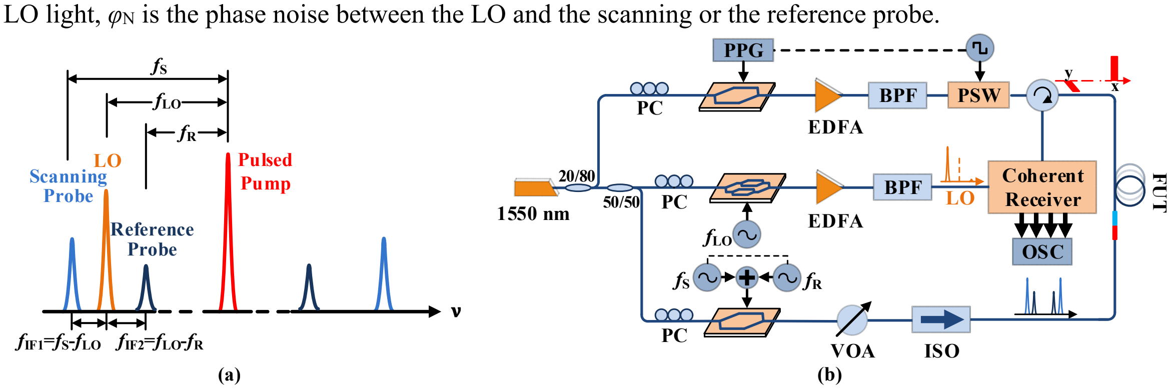

Fig. 1. (a) The frequency relationship of Pulsed pump, Scanning probe, and Reference probe; (b) Experimental setup of the proposed scheme

Fig. 1 (b) shows the experimental setup of the proposed scheme. The output of a 1550 nm laser is split into three branches. The upper branch is used to generate pump pulses with 40 ns width and 21 dBm peak power. A polarization switch (PSW), driven by a function generator synchronized with the pump pulses, enables two sequential Brillouin responses orthogonal to each other to minimize the polarization dependent fluctuations of Brillouin signal. The lower branch produces dual double-sideband probe lightwaves by two synchronized radio frequency (RF) synthesizers. The tunable RF synthesizer provides the frequencies for the scanning probe from 10.73 to 10.9 GHz for the BOTDA system, and the other fixed at 9 GHz is used for the generation of the reference probe. The power of the lower sideband of the scanning and reference probe are about -8 dBm and -14 dBm. An IQ modulator and a frequency-fixed 10 GHz RF synthesizer in the middle branch are used to generate a lightwave as LO using SSB modulation technique for coherent detection. The carrier is suppressed by over 30 dB, the upper side band is suppressed by up to 40 dB, and the total power is amplified to around 10 dBm. The probe lightwaves after propagating in the fiber under test (FUT) and the LO are then injected into a commercial integrated coherent receiver (ICR). The in-phase and quadrature-phase signals of the two orthogonal polarizations are collected by the four channels of a real-time oscilloscope (OSC). A low pass filter (DC-1.3GHz) at each channel is employed to block the unwanted high frequency electrical components.

3. Experimental Results

The FUT is an 18.3 km single-mode fiber with the last 200 m section heated to 40 °C and a 4 m section before the 200 m section placed in iced water. In Fig. 2, the measured Brillouin gain spectrum (BGS) and Brillouin phase-shift spectrum (BPS) distributions are illustrated. The 200 m and 4 m sections are successfully detected from both BGS and BPS distributions. Fig. 3 gives the Brillouin frequency shift (BFS) distributions by using curve fitting methods based on the BGS and BPS distributions. As shown in Fig. 3 (b), the BFS uncertainty of the last 200 m for each distribution is calculated as 0.8376 and 0.9299 MHz, respectively. It can also be seen from Fig. 3 (c) that both BGS and BPS measurements realize the spatial resolution of 4 m. The frequency difference of 40 MHz between the heated and cooled sections agrees well with the temperature difference of 40 °C.

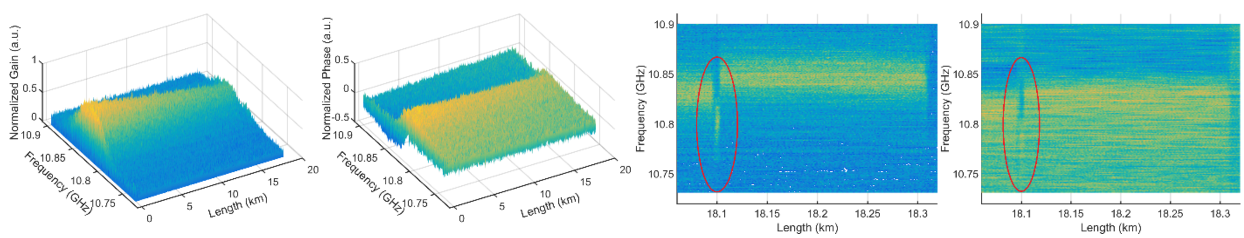

Fig. 2. Measured of (a) BGS and (b) BPS distribution along the whole FUT; (c) BGS and (d) BPS distribution along the last 250 m (top view).

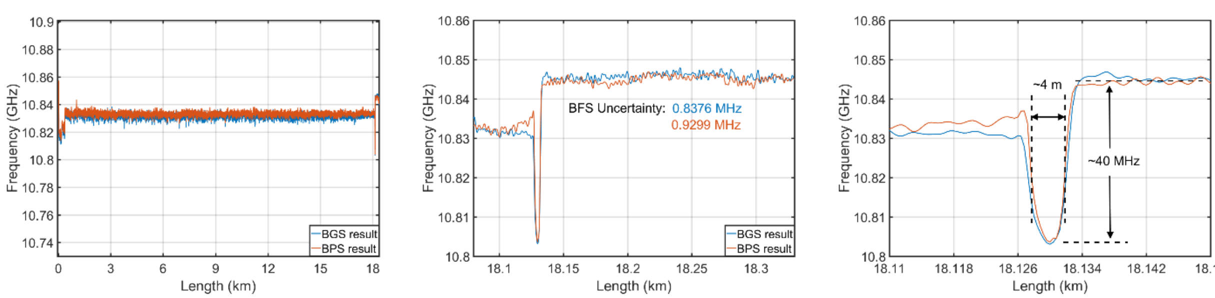

Fig. 3. BFS distributions (a) along the whole FUT, (b) along the last 250 m, and (c) around the location of temperature transition based on BGS (blue curve) and BPS (red curve) measurements.

4. Conclusion

A novel scheme of averaging-free vector BOTDA sensor is proposed and experimentally demonstrated to realize simultaneously distributed BGS and BPS measurements. The measured BFS uncertainties based on BGS and BPS distribution are respectively 0.8376 and 0.9299 MHz, at the end of 18.3 km FUT with 4 m spatial resolution.

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